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## Performance Prediction of a Cyclone Oil Separator

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### ABSTRACT

This paper presents a technique for predicting the performance of a cyclone oil separator. We predicted the oil droplet size distribution in refrigerant gas (R407C) and refrigeration oil using nitrogen and oil. Furthermore, we developed a theoretical analysis model that considered both centrifugal separation and gravity separation, and predicted oil separation efficiency using the Monte Carlo method. The analysis results agreed with the experimental result within an error of 3% at a refrigerant flow rate of 100–600kg/h when the inflow velocity of the oil droplets was about 0.5 times lower than that of the refrigerant gas. In addition, the analysis results showed the ratio of gravity separation and centrifugal separation for the refrigerant flow rates.

### 1. INTRODUCTION

The outflow of refrigeration oil used to lubricate a compressor reduces not only the reliability of the compressor but also air conditioning performance. One method of preventing refrigeration oil from flowing out is the cyclone method. The cyclone method uses technology developed in the field of solid-gas separation and it can separate the solids from gas using centrifugal force several hundreds or thousands times larger than gravity.

However, when the cyclone method is applied to an oil separator, we have to predict the size distribution of the oil droplets flowing into the oil separator from the inflow pipe because the flow state in the pipe is a two-phase flow of refrigerant gas and refrigeration oil. Moreover, because the refrigerant flow rate for the multi-air conditioner in a building changes over a wide range, we must ensure that the oil separation efficiency of the cyclone oil separator from the high flow-rate in which the centrifugal force becomes large to the low flow-rate in which the centrifugal force becomes small.

This paper therefore proposes a technique for easily and effectively predicting the performance of a cyclone oil separator in a wide refrigerant flow rate.

### 2. PREDICTING THE DROPLET DIAMETERS FOR REFRIGERANT GAS AND REFRIGERATION OIL

#### 2.1 Prediction Method for the Oil Droplet Diameters

It is difficult to measure the diameters of oil droplets that flow into the cyclone oil separator using visible glass because the pressure of the refrigerant gas flowing out from the compressor is high. Moreover, because oil droplets attach to the visible glass even if a high pressure-resistant visible glass is used, it is difficult to measure the oil droplet diameters using laser light.

Therefore, we measure the oil droplet diameters using nitrogen and oil and convert them into oil droplet diameters for the refrigerant gas (R407C) and refrigeration oil so that the Weber Number  $We$  of both flows becomes equal. Here, the Weber Number  $We$ <sup>4)</sup> is defined as:

$$We = \frac{\rho_g (j_g - j_l)^2 d}{\sigma}, \quad (1)$$

where  $\rho_g$  and  $j_g$  are density and flow velocity of the nitrogen (or the refrigerant gas), and  $d$ ,  $\sigma$ , and  $j_l$  are diameter, surface tension and flow velocity of the oil (or the refrigeration oil), respectively.

## 2.2 Experimental Apparatus and Experimental Method

Figure 1 shows the experimental apparatus for the nitrogen and oil. The oil that flows out from an oil tank placed on the position at 2000mm in height joins the nitrogen that flows out from the nitrogen gas cylinder at the T-junction. The nitrogen and oil passes through a copper pipe 800mm in length and 17mm in internal diameter, and we measure the diameters of oil droplets that disperse from the edge of the copper pipe with a laser diffraction particle size analyzer (LDSA-2400A, Tohnichi Computer Applications, Japan). We measured the oil flow rate from the oil decrease rate in the oil tank, and the nitrogen flow rate with a flow meter. We also measured the oil flow rate that falls from the edge of the copper pipe with a glass beaker put under the copper pipe. The experimental conditions and the properties are shown in Table 1. The oil used in the nitrogen and oil is selected as the one that has values close to the surface tension and the viscous coefficient of the refrigeration oil. The viscous coefficient of the refrigeration oil is at the value of 100°C and 15% in refrigerant solubility. The refrigerant flow rates of the multi-air conditioners in a building change from 100-600kg/h and the oil flow rate is 2.5wt% of the refrigerant flow rate. We decided that the flow rate of the nitrogen and oil agreed with the flow pattern of the refrigerant gas and refrigeration oil on the Baker's flow pattern map<sup>1)</sup>. The flow pattern of the refrigerant gas and refrigeration oil becomes wavy or annular on the Baker's flow pattern map. The oil droplet diameters of the refrigerant gas and refrigeration oil are about 0.72 times smaller than that of the nitrogen and oil.

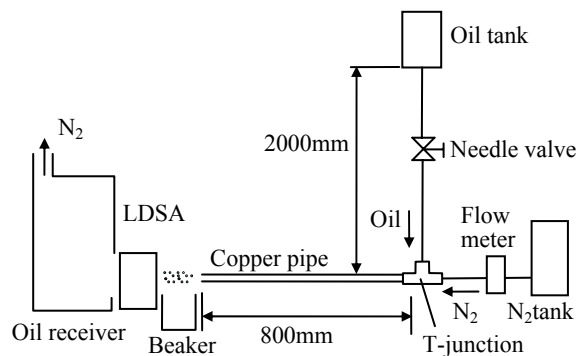


Fig. 1 Experimental apparatus

Table 1 Experimental conditions and properties

Working fluid		N <sub>2</sub> and oil	Refrigerant gas and refrigeration oil
Density	$\rho_g$ [kg/m <sup>3</sup> ]	1.15	66.9
	$\rho_l$ [kg/m <sup>3</sup> ]	867	995
Surface tension	$\sigma$ [N/m]	0.0297	0.0244
Flow rate	$G_g$ [kg/h]	12-73	100-600
Oil concentration	$c$ [wt%]	18.7	2.5
Viscosity	$\mu_g$ [Pa·s]	$1.78 \times 10^{-5}$	$1.66 \times 10^{-5}$
	$\mu_l$ [Pa·s]	7e-3	4e-3

## 2.3 Measurement Results of the Oil Droplet Diameters

Figure 2 shows the oil droplet size distribution measured using nitrogen and oil. We plotted the oil droplet size distribution for the value in which the oil diameter  $d$  was made dimensionless using the arithmetic mean diameter  $d_l$ . Here,  $\Delta n$  is the number of oil droplets that exist in the section from  $(d-\Delta d/2)$  to  $(d+\Delta d/2)$  and  $N$  is the total number of oil droplets. The measurement result can be expressed using the following equation with gamma distribution<sup>4)</sup>:

$$\frac{\Delta n}{N} = 24 \left( \frac{d}{d_l} \right)^{2.27} \exp \left( -3.27 \frac{d}{d_l} \right) \frac{\Delta d}{d_l}. \quad (2)$$

Moreover, as well as the average droplet diameters in the air-water annular flow proposed by Tatterson et al<sup>3)</sup>,  $d_l$  in the expression (2) was expressed as:

$$\frac{d_1}{D_{in}} = 7.43 \times 10^{-3} \left( \frac{\sigma}{\rho_g u_g^2 D_{in}} \right)^{0.5} \left( \frac{u_g D_{in}}{v_g} \right)^{0.1} \quad (3)$$

where  $D_{in}$  is the copper pipe diameter,  $u_g$ ,  $v_g$ , and  $\rho_g$  are flow velocity, dynamic viscosity and density of nitrogen, respectively, and  $\sigma$  is the oil surface tension. Figure 3 shows the arithmetic average of the oil droplet diameters measured using nitrogen and oil. Moreover, Figure 4 shows the ratio of the oil droplet flow rate  $G_d$  to the total oil flow rate  $G_l$  in the nitrogen and oil. Here, we obtain the oil flow rate  $G_d$  by subtracting the oil flow rate  $G_f$  that falls from the edge of the copper pipe from the total oil flow rate  $G_l$ . As well as the liquid flow rate for the descent flow proposed by Wallis<sup>5)</sup>, the ratio of oil droplets for the flow rate  $G_d$  to the total oil flow rate  $G_l$  can be expressed as:

$$\frac{G_d}{G_l} = 0.028 \times G_g - 0.27 \quad (4)$$

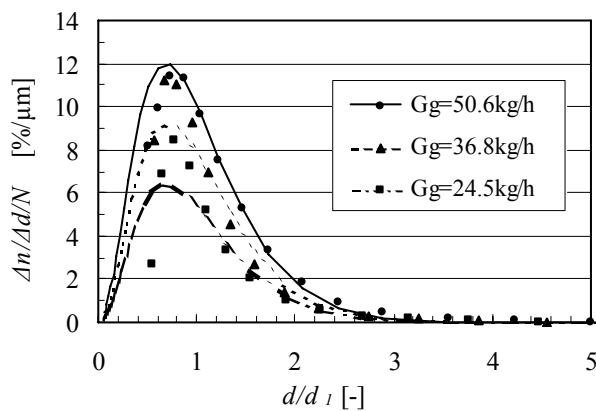


Fig. 2 Oil droplet size distribution

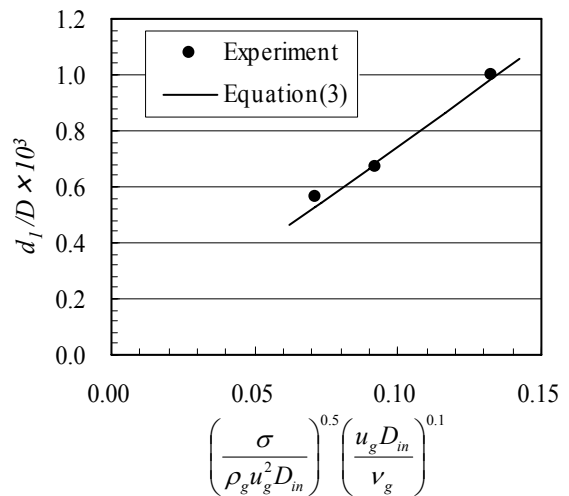


Fig. 3 Arithmetic average oil droplet diameters

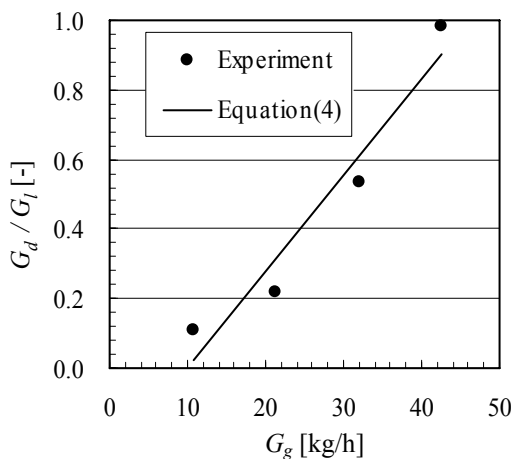


Fig. 4 Oil droplets flow rate

### 3. ANALYSIS MODEL

#### 3.1 Centrifugal Separation Model

Figure 5 illustrates the centrifugal separation model. The two-phase flow of the refrigerant gas flow rate  $G_g$  and the refrigeration oil flow rate  $G_l$  pass through the inflow pipe with a diameter  $D_{in}$  and then flow into the cyclone oil separator with a diameter  $D$ . Some of the refrigeration oil then becomes oil droplets with a diameter  $d$  and a velocity  $u_d$ , and they disperse from the position at a distance  $w$  from the wall of the cyclone oil separator, moving downward while turning. The oil droplet velocity  $u_d$  changes in the range of the refrigerant velocity  $u_{gin}$  to the refrigeration oil velocity  $u_{lin}$ . We calculated the refrigerant velocity  $u_{gin}$  and the refrigeration oil velocity  $u_{lin}$  using Smith's void fraction equation<sup>2)</sup>. The centrifugal separation condition of oil droplets is expressed as:

$$L_a \leq E, \quad (5)$$

where  $L_a$  is the downward distance when the oil droplet attaches to the wall of the cyclone oil separator and  $E$  is the length from the center of the inflow pipe to the edge of the outflow pipe. When the distance  $L_a$  is smaller than the length  $E$ , oil droplets separate from the refrigerant gas and attach to the wall of the cyclone oil separator. Here, the distance  $L_a$  is given by the following equations:

$$L_a = u_c \times t_a, \quad (6)$$

$$u_c = \frac{4G_g}{\rho_g \pi (D^2 - D_{out}^2)}, \quad (7)$$

where  $u_c$  is the average downward velocity of the refrigerant gas,  $t_a$  is the time required to move from the position of distance  $w$  to the wall of the cyclone oil separator, and  $D_{out}$  is the outflow pipe diameter. The radial equation of motion for an oil droplet can be expressed as:

$$\frac{\pi}{6} \rho_d d^3 \frac{du_r}{dt} = -C_D \left( \frac{\pi d^2}{4} \right) \left( \frac{\rho_g u_r^2}{2} \right) + \frac{\pi}{6} \rho_d d^3 (\rho_d - \rho_g) \frac{u_d^2}{r} \quad (8)$$

where  $u_r$  is the radial velocity of the oil droplet and  $C_D$  is the drag force coefficient. Moreover, because the Reynolds number  $Re_d$  based on the oil droplet diameter is smaller than 1, the drag force coefficient  $C_D$  is expressed as:

$$C_D = \frac{24}{Re_d}. \quad (9)$$

In addition, because the oil droplet diameter is  $\mu\text{m}$  order or less, the acceleration term in equation (8) is omitted and we obtain the following expression:

$$u_r = \frac{dr}{dt} = \frac{(\rho_d - \rho_g) d^2 u_d^2}{18 \mu_g r}. \quad (10)$$

Time  $t_a$  is obtained from the integration of equation (10).

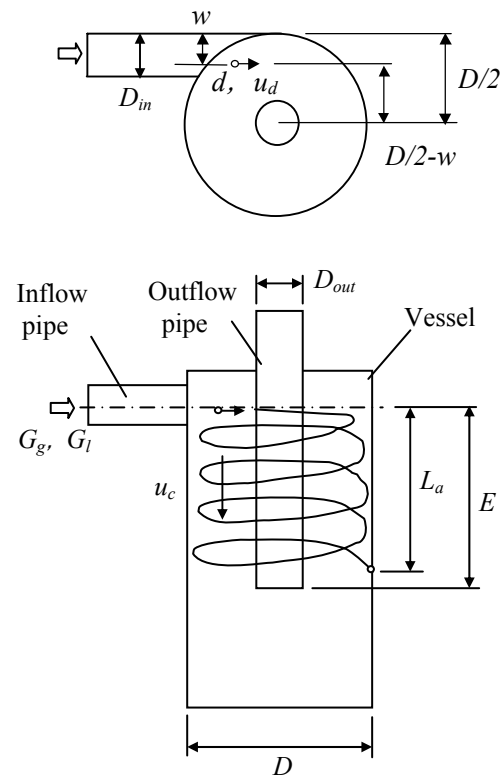


Fig.5 Centrifugal separation model

$$\int_{D/2-w}^{D/2} r dr = \frac{(\rho_d - \rho_g)d^2}{18\mu_g} u_d^2 \int_0^{t_a} dt, \quad (11)$$

$$t_a = \frac{18\mu_g}{(\rho_d - \rho_g)d^2 u_d^2} \frac{w(D-w)}{2}. \quad (12)$$

Therefore, distance  $L_a$  is determined by combining equation (6), equation (7) and equation (12).

$$L_a = \frac{18\mu_g}{(\rho_d - \rho_g)d^2 u_d^2} \frac{w(D-w)}{2} \times u_c. \quad (13)$$

### 3.2 Gravity Separation Model

Figure 6 shows the gravity separation model. The gravity separation model is applied to those oil droplets that aren't separated using the centrifugal separation model. The oil droplets that aren't separated by the centrifugal separation model exist at the radial distance  $r_b$  from the center axis when it reaches the same height as the edge of the outflow pipe. Then, the oil droplets move to the center axis due to gravity. The gravity separation model is expressed as:

$$L_b \geq H, \quad (14)$$

where  $L_b$  is the downward moving distance of the oil droplets when they move from the radial position  $r_b$  to the center axis and  $H$  is the distance from the edge of the outflow pipe to the bottom of the cyclone oil separator. When distance  $L_b$  is larger than distance  $H$ , the oil droplets attach to the bottom of the cyclone oil separator and separate from the refrigerant gas. As shown in Figure 7, although the actual oil droplets move from position (a) to position (b) due to gravity and drag force, distance  $L_g$  is expressed by the following equation, which considers the radial movement and the downward movement separately:

$$L_b = u_y \times t_b, \quad (15)$$

where  $u_y$  is the downward velocity of the oil droplets and  $t_b$  is the time required to move from position (a) to position (c). We assume that the oil droplet velocity  $u_r$  toward the center axis is equal to the refrigerant gas velocity that passes through the surface of a hemisphere.

$$u_r = -\frac{dr}{dt} = \frac{G_g}{\rho_g \times 2\pi r^2}. \quad (16)$$

We obtain time  $t_b$  by integrating equation (16).

$$-\int_{r_b}^0 r^2 dr = \frac{G_g}{2\pi\rho_g} \int_0^{t_b} dt, \quad (17)$$

$$t_b = \frac{2\pi\rho_g r_b^3}{3G_g}. \quad (18)$$

The equation of motion for an oil droplet in the downward direction can be expressed with the drag force coefficient  $C_D$ , which is similar to equation (9):

$$\frac{\pi}{6} \rho_d d^3 \frac{du_y}{dt} = -6\pi\mu_g \left(\frac{d}{2}\right) (u_y + u_{gout} - u_c) + \frac{\pi}{6} d^3 (\rho_d - \rho_g) g, \quad (19)$$

where  $u_{gout}$  is the downward velocity induced by the outflow of refrigerant gas. We obtain the downward velocity  $u_y$  using the following expression when the oil droplet diameter is  $\mu\text{m}$  order or less.

$$u_y = \frac{(\rho_g - \rho_d)d^2}{18\mu_g} g - u_{gout} + u_c. \quad (20)$$

Therefore, we determine the downward distance  $L_b$  by combining equation (15), equation (18) and equation (20).

$$L_b = \frac{2\pi\rho_g r_b^3}{3G_g} \left( \frac{(\rho_g - \rho_d)d^2}{18\mu_g} g - u_{gout} + u_c \right). \quad (21)$$

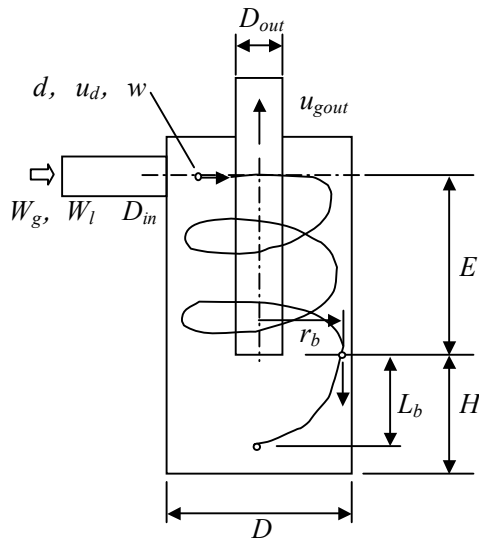


Fig. 6 Gravity separation model

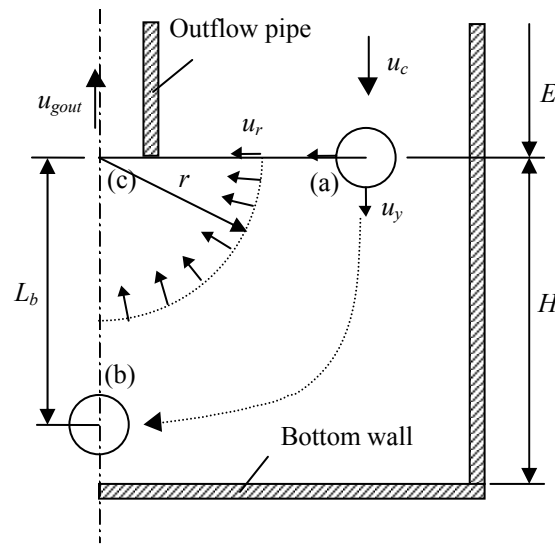


Fig. 7 Enlarged figure of gravity separation model

### 3.3 Prediction Technique for Oil Separation Efficiency

The oil separation efficiency  $\eta$  is obtained as:

$$\eta = \frac{G_d \times \varepsilon + G_f}{G_l} \times 100, \quad (22)$$

where  $G_d$  is the oil droplet flow rate,  $G_f$  is the oil flow rate that falls from the edge of the copper pipe, and  $G_l$  is the total oil flow rate.  $\varepsilon$  is the probability that oil is separated using the centrifugal separation model or the gravity separation model and it is expressed as

$$\varepsilon = \frac{M_a + M_b}{M_{all}}, \quad (23)$$

where  $M_a$  is oil droplet mass separated using the centrifugal separation model,  $M_b$  is oil droplet mass separated using the gravity separation model, and  $M_{all}$  is the total oil droplet mass used for the separation judgment. We calculate  $\varepsilon$  using the Monte Carlo method that gives the oil diameter  $d$  and the dispersed oil position  $w$  as random numbers.

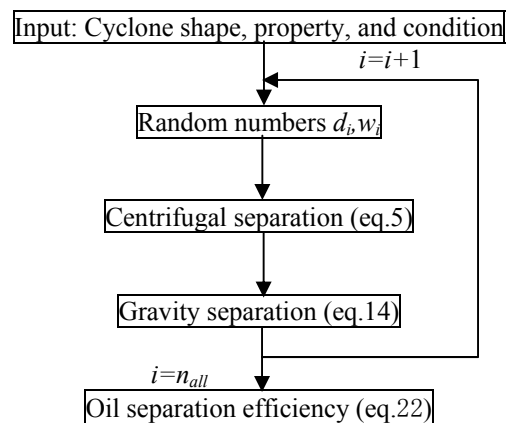


Fig. 8 Flow Chart

Figure 8 shows the flow chart. Firstly, we input the shape of the cyclone oil separator, the properties and the operating conditions. Next, we give the oil diameter  $d_i$  and dispersed oil position  $w_i$  as random numbers and execute the centrifugal separation model and the gravity separation model. We calculate the oil separation efficiency when the total number of oil droplets reaches  $n_{all}$ . If the total number of oil droplets is more than 10000, the oil separation efficiency is almost stable.

#### 4. ANALYSIS RESULTS

Figure 9 shows the experiment and analysis results of the oil separation efficiency for the refrigerant gas and refrigeration oil. The shape of the cyclone oil separator has a diameter  $D=76.2\text{mm}$ , a length of  $E=120\text{mm}$  and  $H=100\text{mm}$ , an inflow pipe diameter of  $D_{in}=17\text{mm}$ , and an outflow pipe diameter of  $D_{out}=17\text{mm}$ . The experiment results show that the oil separation efficiency decreased when the refrigerant flow rate increased in the range of 100-400kg/h. Furthermore, the oil separation efficiency increased when the refrigerant flow rate increased by more than 400kg/h. The oil separation efficiency of this cyclone oil separator was the lowest at a refrigerant flow rate of 400kg/h and it was more than 92% at a refrigerant flow rate of 100-600kg/h. The oil droplet velocity  $u_d$  was defined as:

$$u_d = k \times u_{gin} \quad (u_{lin} / u_{gin} \leq k \leq 1), \quad (24)$$

where  $u_{gin}$  and  $u_{lin}$  are the inflow velocities of the refrigerant gas and refrigeration oil, respectively. The analysis results agreed with the experimental result within an error of 3% at a refrigerant flow rate of 100-600kg/h when the inflow velocity of the oil droplets was about 0.5 times lower than that of the refrigerant gas. We think that the inflow velocity of the oil droplets became lower because the cross section increased from inflow pipe to the cyclone oil separator.

Figure 10 shows the ratio of the centrifugal separation and the gravity separation at refrigerant flow rates of 300, 400, and 500kg/h. The ratio of the gravity separation in the refrigerant flow rate 300kg/h was about 40% and the ratio of the centrifugal separation increased as the refrigerant flow rate increased. We think that the oil separation efficiency using gravity separation improved in the low refrigerant flow rate because the flow rate of oil that falls from the edge of the inflow pipe increased. Furthermore, we assume that the oil separation efficiency using centrifugal separation improved in the high refrigerant flow rate because the centrifugal force that acted on the oil droplets increased.

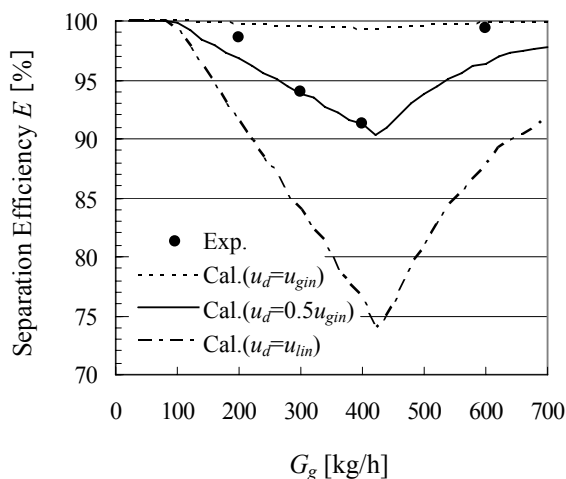


Fig. 9 Oil separation efficiency

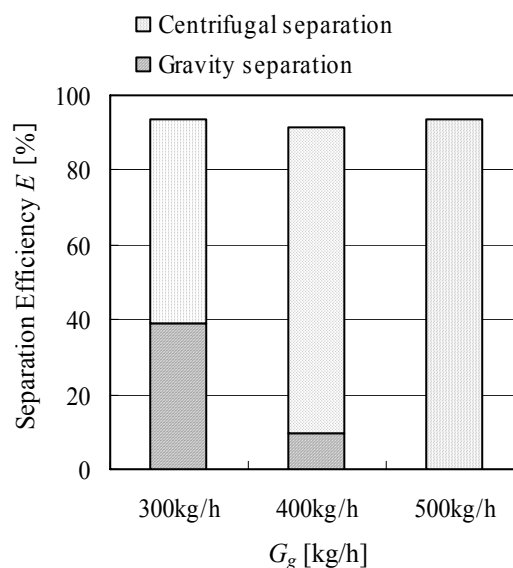


Fig. 10 Ratio of centrifugal separation and gravity separation



## 5. CONCLUSIONS

We predicted the diameter size distribution of oil droplets in refrigerant gas and refrigeration oil from the experiment using nitrogen and oil. In addition, we developed a performance prediction technique for the cyclone oil separator considering both centrifugal separation and gravity separation, and we predicted oil separation efficiency using the Monte Carlo method. The analysis results agreed with the experimental results within an error of 3% at a refrigerant flow rate of 100-600kg/h when the inflow velocity of the oil droplets was about 0.5 times lower than that of the refrigerant gas. Furthermore, we clarified the ratio of centrifugal separation and gravity separation in the oil separation efficiency.

## NOMENCLATURE

$C_D$	drag force	(-)	<b>Subscripts</b>
$d$	droplet diameter	(m)	$a$ centrifugal separation
$D$	diameter of oil separator or pipe	(m)	$all$ total number of oil droplets
$G$	mass flow rate	(kg/h)	$b$ gravity separation
$M$	oil droplet mass	(kg)	$d$ oil droplet
$n$	number of oil droplets	(-)	$g$ nitrogen or refrigerant gas
$Re$	Reynolds Number	(-)	$in$ inflow pipe
$r$	radial distance	(m)	$l$ oil or refrigeration oil
$t$	time	(s)	$out$ outflow pipe
$u$	flow velocity	(m/s)	$r$ radial direction
$w$	dispersed oil position	(m)	$y$ downward direction
$We$	Weber Number	(-)	
$\sigma$	surface tension	(N/m)	
$\rho$	density	(kg/m <sup>3</sup> )	
$\nu$	dynamic viscosity	(m <sup>2</sup> /s)	
$\mu$	viscosity	(Pa·s)	
$\eta$	oil separation efficiency	(%)	

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